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INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(51) International Patent Classification 6 : H01J	A2	(11) International Publication Number: **WO 95/30235** (43) International Publication Date: 9 November 1995 (09.11.95)

(21) International Application Number: PCT/US95/05185

(22) International Filing Date: 25 April 1995 (25.04.95)

(30) Priority Data:
08/232,764 25 April 1994 (25.04.94) US

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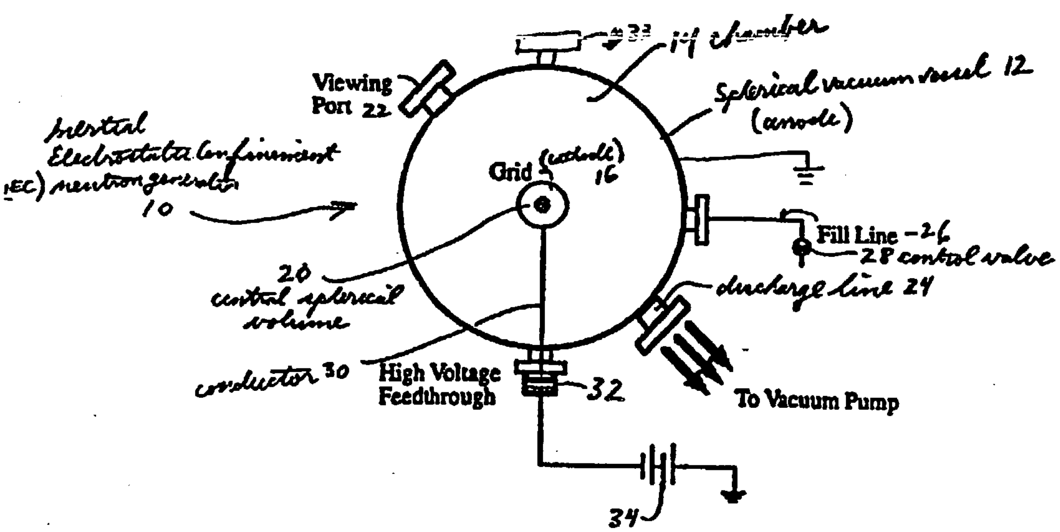
(81) Designated States: AU, European patent (AT, BE, CH, DE, DK, ES, FR, GB, GR, IE, IT, LU, MC, NL, PT, SE).

Published
Without international search report and to be republished upon receipt of that report.

(54) Title: INERTIAL-ELECTROSTATIC CONFINEMENT PARTICLE GENERATOR



(57) Abstract

An apparatus for generating neutrons and protons which includes a vacuum vessel having anode means substantially within vacuum vessel. The apparatus further includes at least one cathode wire grid which defines a central volume and is concave towards a central region of the vacuum vessel. The cathode wire grid is permeable to gas and to ions and disposed between the anode means. The apparatus further includes a means for introducing controlled amounts of reactive gas into the vacuum vessel and the central volume to obtain an internal pressure of the vacuum vessel. Finally, the apparatus includes means for applying an electric potential between the anode means and the cathode wire grid to produce a glow discharge caused by ions produced between the anode means and the cathode wire grid. The glow discharge is substantially determined by design criteria of the cathode wire grid and the internal pressure of the vacuum vessel.

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INERTIAL-ELECTROSTATIC CONFINEMENT PARTICLE GENERATOR

Background of the Invention

Field of the Invention

This invention relates to a particle generator and, more particularly, to a neutron and proton generator that confines a controlled nuclear fusion reaction inside a negative potential well structure.

Description of the Priot Art

Experimental work has been done on inertial-electrostatic confinement ("IEC") devices. One such experimental study employed ion-gun injectors which demonstrated the ability to generate approximately 10^9 D-T neutrons per second at maximum currents and voltages established by grid-cooling requirements and voltage breakdown limits. The ion guns employed special characteristics which are illustrated in U.S. Patent 3,448,315 issued to R. L. Hirsch, et al. The '315 patent discloses an improvement for forming and directing a beam of ions from a chamber with increased efficiency.

U.S. Patent 3,386,883 issued to P. T. Farnsworth discloses ion guns mounted around a spherical anode which surrounds a spherical cathode. Ions from the guns are focused into the center of the cathode. U.S. Patent 3,258,402, also issued to P. T. Farnsworth, was an earlier version which discloses a spherical cathode surrounding a spherical anode. This patent suggests that with a proper choice of materials for the cathode, the central gas may be ionized by electron emission from the cathode, thus eliminating the need for ion guns. This appears to be merely a theoretical suggestion.

U.S. Patent 3,530,497 issued to Hirsch, et al., also illustrated a spherical anode which had concentrically positioned therein an ion-source grid and a cathode, both spherical and permeable to charged particle flow. However, as illustrated in this patent, both the spherical cathode and the ion-source grid are required and the ion-source grid is placed between the cathode and the anode. Varying potentials

are applied to each of the three electrodes, thus establishing a first electric field in the space between the anode and the ion-source grid, and a second electric field in the space between the ion-source grid and the cathode. Ions formed inside the ion-source grid are propelled toward the centrally located cathode due to the potential difference. These ions are focused toward the center of the inside of the cathode and interact, thereby producing a fusion reaction. One disadvantage of this device is that it requires an ion-source grid in addition to the spherical cathode and anode. Furthermore, a thermionic cathode is required in the space between the outer anode and the ion-source grid, such that electrons from the thermionic cathode will flow toward the grid rather than to the outer anode. With the addition of each element, the complexity and cost of the apparatus increases.

Applicants participated in preparing papers entitled "Advantages of Inertial-Electrostatic Confinement Fusion," published in *Fusion Technology*, Vol. 20, p. 850, December 1991 and "Characterization of an Inertial-Electrostatic Confinement Glow Discharge (IECGD) Neutron Generator," published in *Fusion Technology*, Vol. 21, p. 1639, May 1992. These papers reported studies of devices based on the studies reported by Hirsch and Farnsworth in their patents cited above.

A problem with the prior art IEC devices is that they are expensive to manufacture, are bulky, and require precise alignment of components, such as ion guns, in order to operate properly. With these complications, their use was intended for higher-intensity applications, viewed as leading to a fusion energy source, which implies associated neutron emission rates above 10^{14} n/s. other applications require a lower-intensity source which is typically met using radioisotope neutron sources, e.g. Cf-252. However, disadvantages of such radioisotopes include their relatively short half lives and the broad energy spectrum of their emitted neutrons. Another problem with the radioisotope design is

that it does not have an on/off capability. Thus, the source must be stored in bulky protective shielding when not in use. Further, Cf-252 must be produced using a high-flux fission reactor, making it expensive and, due to a reduction in such reactors operating in the U.S. in recent years, fairly scarce. Thus, there is a strong motivation to seek other types of neutron sources, such as the applicants disclose herein.

Another alternate low-intensity neutron source uses a miniature deuteron accelerator to bombard a solid target implanted with tritium. (R. C. Smith, et al., *IEEE Trans. on Nuc. Sci.*, 35, 1, 859 [1988].) Currently available small (i.e. , 10^6 - 10^8 n/s time average) neutron generators of this type use a titanium target embedded with deuterium or a deuterium-tritium mixture. The device typically operates in a short-pulse mode with a moderate repetition rate in order to avoid overheating of the target. Versions of this concept with higher neutron intensities have been built using a high-speed rotating target to prevent overheating, but these devices are very expensive.

Disadvantages of such generators using a deuteron beam and a solid target are that they are pulsed generators, have relatively short operating times until maintenance is necessary, and require tritiated targets which mandate compliance with radioisotope-handling regulations. As such a generator is used, the target's effectiveness typically decreases with time, until it is ultimately exhausted and must be replaced. The target is relatively expensive and must be replaced after several hundred hours of operation. This type of generator also has the storage and disposal problems associated with radioisotope sources.

The invention disclosed herein is intended to overcome most of the disadvantages of these various low-intensity neutron sources.

Summary of the Invention

There is provided a vacuum vessel which is held at ground potential. Concentric to the vessel, and mounted inside the chamber, is a wire grid which acts as the cathode means. The cathode grid can be made from stainless steel, molybdenum, tungsten, or other high-temperature materials with good structural strength and appropriate secondary electron and thermionic electron emission coefficients. The cathode wire grid is connected to a power source to provide a high negative potential on the order of 30 kV to 70 kV. Deuterium, or a mixture of deuterium and tritium gas, is introduced into the vessel so that the background pressure is on the order of 10^{-3}-10^{-2} Torr.

Two methods of operation are possible. In one, the gas or gas mixture is continuously introduced and extracted from the chamber, providing a flow system. Alternately, a static fill of gas or gas mixture can be introduced and the chamber sealed off to maintain the desired internal pressure. In the latter case, operation time is set at 10s of hours by impurities sputtered off of the grids by the high-energy ions. Gettering techniques can be employed to lengthen this time if necessary. To restart the device, the seal is broken, and it is reconnected to a vacuum system, pumped down, and filled with fresh gas or gas mixture. An advantage of sealed operation is that the elimination of a connected vacuum-pump system enhances portability. The voltage is applied to the cathode wire grid and the pressure is adjusted in such a manner as to initiate a glow discharge.

To maximize the neutron yield per unit power input while maximizing grid life-time by reducing collisions with the grid, operational conditions and designs are sought to create special glow discharge modes (the Star and/or Halo modes) described later. The resulting glow discharge generates ions, which are extracted from the discharge by the electric field created by the cathode grid. These ions are accelerated through the grid openings and focused at a spot in the center of the spherical device. The resulting high-

energy ions interact with the background gas (beam-background collisions) and themselves (beam-beam collisions) in a small volume around the center spot, resulting in a high rate of fusion reactions. The result is a neutron generator producing neutrons on the order of 10^6-10^8 neutrons per second. In devices using even higher injection rates, the injected ions may provide a deep self-generated potential well that confines trapped beam ions, creating even higher reaction rates.

The device may be modified by using a fill gas mixture of deuterium and helium-3 to be a source of protons as well as neutrons. (The deuterium filled device also produces 3.02 MeV protons along with 2.45 MeV neutrons. However, the proton energy is significantly lower than that obtained in the deuterium--helium-3 version (14 MeV) , making it harder to extract them through a thin metallic window, as is described later for the deuterium--helium-3 case.) Two geometrical forms of the device have been developed--one spherical and the other cylindrical, and both are described here, since each has its own unique features and advantages for certain applications.

Objects of the Invention

It is an object of the invention to provide an apparatus for generating a fusion reaction resulting in a particle generator with an output of 10^6-10^8 neutrons per second. It is a related object to provide a neutron generator having the above output which can be switched on or off.

It is another object to choose materials and geometry such that ion current can be maximized while maintaining the structural integrity of the grid with radiative cooling alone. This prevention of grid overheating avoids the complication of active cooling requirements, e.g. by forced convection of a fluid through a tubular grid design.

Still another object is to achieve the maximum transparency permitted, while still allowing operation in the special Star and Halo discharge modes noted earlier. The

combination of high transparency and utilization of these modes provides minimum ion bombardment of the grids. Structural strength and the adequate, but not excessive, secondary electron production at the grid (to partly space-charge neutralize the ion beams) are also objects of the invention. Some control of secondary electron emission is obtained by the grid materials, including the possible use of composite and/or coated materials to effect the secondary electron production coefficient associated with particle bombardment at higher temperatures. The thermionic emission properties of the grid material also play an important role in its selection. Finally, there may- be trade-offs among these factors to minimize bombardment and evaporation of the grid material in order to maximize its lifetime.

It is another object to provide a source of neutrons with nearly isotropic angular distribution emitted from a small volume, to a first approximation approaching an isotropic point source. Also, since fusion neutrons are emitted and little material intercepts them prior to leaving the chamber, a nearly monoenergetic source in energy is obtained, centered around 2.5 MeV if deuterium fill gas is used. An intense 14.1-MeV neutron source is obtained when a mixture of deuterium and tritium is employed. Due to the larger fusion cross section for deuterium and tritium, neutron emission rates for this device will be about two orders of magnitude higher than for an equivalent deuterium device. However, the use of radioactive tritium poses the added complication of requiring radiation protection licensing for its use.

Yet another object is to provide a neutron generator which can emit fusion neutrons and be self-calibrating. A related object is to provide a neutron generator that is simple in its operation and construction, sturdy in its design and is a low-cost fusion neutron source.

Still another object is the object of providing a neutron generator having all of the above objects yet being easily portable.

Another object is to provide a neutron generator which does not use a radioisotope neutron source. The inherent disadvantage of radioisotope neutron sources are that they have relatively short half lives, the neutrons emitted have a broad energy spectrum, and the source must be stored in protective shielding when not in use.

It is another object to provide a neutron generator that does not use a conventional accelerator-solid target design. Such solid target designs have the disadvantage of high maintenance, being a pulsed as opposed to a steady-state generator and requiring the use of a tritiated target. Their lifetimes are also limited by gradual loss of gaseous tritium from the target and by tritium decay (12.5-year half-life).

It is another object to provide an inertial electrostatic confinement-based generator in which the glow discharge functions as an ion-source. A highly transparent spherical grid, biased to (negative) kV potentials, serves to extract and accelerate ions from the glow discharge plasma and focuses the resulting ion beams at the center of the spherical chamber.

It is another object to provide an independent calibration of the neutron emission rate, using a solid-state detector to simultaneously record the deuterium fusion proton emission rate.

Yet another object is to provide a generator for high-energy (MeV) protons at rates roughly equivalent to those for neutrons. This object would share most operational features with the neutron generator, the main difference being the gas fill employed, and the design of a window region in the vacuum vessel wall where the protons can be extracted for external use.

It is another object to design a vacuum chamber with special structures and/or ports such that objects to be bombarded by protons can be located in a volume around either the inside or the outside of the vacuum chamber wall. The problem is to provide adequate support structures to allow

thin (few millimeters) metallic windows that can pass 14-MeV protons without excessive energy loss.

Another object is to provide a high-performance cylindrical configuration in addition to the spherical embodiment. A cylindrical neutron source may be better suited for some applications, e.g. where the source is to be inserted into a pipe or bore hole. The spherical configuration relies on three-dimensional focusing of the ion beams to obtain a high neutron source rate (proportional to density squared), but only two-dimensional radial focusing seems natural for cylindrical geometry. Consequently, to preserve three-dimensional-like focusing, several unique design features, such as a curved anode plate located on the major axis and a hollow cylindrical cathode centered on the axis, are employed in the cylindrical embodiment.

Brief Description of the Drawings

FIG. 1 is a diagrammatic illustration of a spherical inertial-electrostatic confinement-based neutron generator in accordance with the invention.

FIG. 2 is a potential distribution graph showing the electrical potential across the inertial-electrostatic confinement generator of FIG. 1.

FIG. 3 is a diagrammatic illustration of the generator of FIG. 1 showing the configuration of the wire grid anode.

FIG. 4 is a diagrammatic illustration of the glow discharge in the Central Glow mode.

FIG. 5 is a diagrammatic illustration of the glow discharge in the Star mode.

FIG. 6 is a diagrammatic illustration of the glow discharge in the Halo mode.

FIG. 7 is a diagrammatic illustration of an alternate embodiment of the device shown in FIG. 1 with the addition of a second wire grid.

FIG. 8 is a graph illustrating the variation of neutron output versus cathode voltage for three current levels in a spherical embodiment.

FIG. 9 is a diagrammatic illustration of an alternate embodiment showing a cylindrical generator.

FIG. 10 is a graph illustrating the variation of neutron yield with cathode voltage at several current levels in a cylindrical embodiment.

Description of the Preferred Embodiment

Turning first to FIGS. 1, 2, 3 and 8, there is illustrated an inertial-electrostatic confinement (IEC) neutron and proton generator 10 of the present invention. There is a spherical vacuum vessel 12 preferably made of stainless steel. The vessel 12 is held at ground potential. Inside the vessel 12 is a chamber 14. Concentric to the vessel 12 and mounted inside the chamber 14 is a wire grid cathode 16. For ease of fabrication, the wire grid cathode 16 is preferably made of stainless steel wire, but other materials such as molybdenum or tungsten have been used. Also, flat ribbons have been successfully employed in place of wires for the grids. Ribbons offer the advantage of a larger area for radiative cooling, but are more difficult to manufacture. Depending on the wire diameter selected, the cathode grid 16 has a geometric transparency of between 78% and 99%, with an estimated deviation of less than 3% from exact sphericity. Stated another way, the wires occlude 1% to 22% of the surface area of the sphere which they define. There are holes or openings 18 in the grid 16 which are uniform in size. The wire grid 16 is self-supporting and does not use any internal supporting members. Thus, a central spherical volume 20 is defined by the wire grid 16 which is free from any internal supporting members. The grid 16 is centered in the vessel by electrically insulating members (not shown) extending from the vacuum vessel 12 to the grid 16. The grid's main support is through a high-voltage connector wire 30, which connects to grid 16 and

passes out through the vessel 12 using a high-voltage vacuum lead through an insulator 32.

The IEC generator 10 is provided with a viewing port 22 through which the chamber 14 and grid 16 can be observed. A discharge line 24 is connected from the vessel 12 to a vacuum pump so that the vessel 12 can be evacuated down to about 10^{-7} Torr to minimize residual gas impurities. External heating of the chamber may also be employed to release impurities imbedded in the vacuum vessel wall. Additional ports are provided as required to install diagnostic devices, such as pressure gauges, plasma probes, etc. For self-calibration, one port 33 contains a solid-state detector 35 to measure deuterium fusion protons simultaneously with deuterium fusion neutron generation. Since the deuterium fusion reaction produces one 3.02-MeV proton for each neutron released, a record of the deuterium fusion proton emission rate serves as an independent verification of the deuterium neutron emission rate and provides a built-in calibration of the neutron emission rate. Solid-state proton detectors which measure the rate at which protons are generated and the energy distribution are conventional pieces of equipment. An appropriate unit, Intertechnique Type IPE-80-450-16-EBF, consists of a solid-state diode which is normally reverse biased to prevent current from flowing across the junction from the donor region to the acceptor region. When a proton invades the region and ionizes the background silicon atoms, current flows across the junction and is used to produce a signal indicative of the number and energy of protons generated. To protect the diode from x-rays generated by electron collisions with structures in the device, a thin covering "window" of aluminum or other appropriate material is placed in front of the diode. This absorbs the relatively soft x-rays but passes energetic protons with minimal energy loss.

Through a fill line 26 and control valve 28 deuterium gas is introduced into the chamber 14. Alternatively, the gas can be a mixture of deuterium and tritium, or

deuterium and helium-3. The pressure in the chamber 14 can be adjusted by means of the vacuum pump and control valve 28.

The discharge line 24 is adapted to be disconnected from the vessel 12 once the proper amount of gas has been introduced into the chamber 14. The chamber 14 is sealed as soon as it is disconnected from the line 24 to maintain the vacuum. This permits the vessel 12 to operate independently of the vacuum pump.

The wire grid cathode 16 is connected by means of conductor 30 through the insulator 32 to a negative potential power source 34. The power source should be capable of producing a negative potential of between 10 kV to 80 kV. FIG. 2 shows the electrical potential distribution along a diameter of the vessel 12. FIG. 8 shows the variation of neutron output with cathode voltage for three current levels.

In an alternate embodiment, as seen in FIG. 7, a second larger grid 36 is mounted between the grid 16 and vessel 12 and concentric with the cathode grid 16. The second grid 36 is biased slightly negative to about 25% of the cathode grid potential. The grid wires of the larger grid 36 are positioned between the grid wires of the cathode 16 as viewed along radii of the grids and vessel. This produces the Central Glow discharge mode shown in FIG. 4. While superficially similar to multigrid configurations disclosed by Farnsworth and Hirsch, the present device differs in that neither ion guns nor special electron emitters are incorporated, so most "excess" electrons come from collisions of ions from the central glow discharge with the grids.

In another embodiment, as seen in FIGS. 9 and 10, there is an outer vacuum vessel 40 which is cylindrical rather than spherical. Also, the vacuum vessel 40 is preferably made from an electrical insulator such as glass rather than from stainless steel. There are a pair of concave dish-shaped anodes 42,44 which maintain spherical focusing of the ion beams, hence, a spherical plasma core region 45. The anodes 42,44 are formed from steel plates which are mounted

to supports 46 at the ends of the vessel 40. There is a cathode 48 which is formed from a cylindrical steel mesh or grid supported by rings 50 and spacers 51. The cathode 48 is connected to a high negative voltage on the order of 30 kV to 80 kV with a driving current of 1 mA to 100 mA. A gas such as H_2, D_2 or N_2 is supplied to the vessel 40 from inlet 52 and discharged through outlet 54. The discharge outlet 54 is connected to a vacuum pump which operates as described for the spherical vacuum vessel 12. The high voltage bias creates a gas breakdown, and a plasma discharge is formed in the region between the anode plates 42,44 and cathode 48. Ions created in this fashion are accelerated by the cathode into the main plasma core region 45 (i.e. inside the cylindrical cathode) where they collide with the background gas. If D_2 gas is used, this produces a source of neutrons due to D-D fusion reactions created in the collision process. Some of the electrons created in this fashion are accelerated by the anode and collide with its plates, producing x-rays. The object of this invention is neutron production, but since x-rays are also produced that may partially escape through the vessel walls, both radiations must be considered in the design of protective procedures for the operation.

Many details of the operation of the device are similar to the spherical device. However, the selection of optimum operating pressures and currents differ somewhat, and the differences in the geometry and vacuum-chamber material result in some differences in the neutron and x-ray source strengths. The most striking change is that the glass chamber in the cylindrical device does not attenuate x-rays as well as the steel chamber used for the spherical device. Hence, added lead shielding should be used to provide x-ray attenuation equivalent to that obtained from the spherical device. With this modification, the operation of the cylindrical device is similar enough to the spherical device that the same radiation protection procedures and operating procedures are used for both devices. This has the advantage that operators only need to learn one procedure so that

errors are less likely. Since the chamber is made of glass, large potentials can be applied to the electrodes without major concerns about corona discharges.

When D_2 gas is used in the cylindrical device in a vacuum analogous to that in the spherical device, mono-energetic neutrons are produced by D-D fusion reactions. The maximum neutron yield measured to date is 10^6 n/s at maximum voltage and ion current of 60 kV and 20 mA, respectively. These results, i.e. neutron rate vs. voltages for several different ion currents, is shown in FIG. 10. The neutron yield is expected to increase to 10^7 n/s at 100 kV, 25 mA, with the present device dimensions. At 6 0 kV, the energy spectrum of the x-rays has an end-point energy of <50 keV, and peak energy of <20 keV.

In a specific embodiment, the cylindrical device consists of a cylindrical glass vacuum chamber. It is 10.16 cm in diameter and 60.96 cm long. Inside the chamber there are one cylindrical stainless-steel cathode tube and two anode stainless steel spherical dish reflectors. The cathode tube is 8.89 cm in diameter and 10.16 cm in length. The anode dish-reflectors are 8.89 cm in diameter. The cathode tube is located in the middle of the glass cylinder. It is electrically connected to a negatively-biased high-voltage power supply through a feedthrough attached to the midpoint of the chamber wall. The two anode reflectors are located symmetrically at the ends of the chamber with respect to the cathode tube. They are electrically grounded.

In operation, first the chamber is evacuated to 10^{-7} Torr pressure and then backfilled with fusible gas to approximately 10^{-3} Torr. The gas pressure is dependent on operation voltage. Second, high-negative voltage is biased to the cathode tube. This high voltage will cause gas breakdown, separating ions from electrons in neutral atoms. The separated ions and electrons are then accelerated along the direction of the electric field created by the high voltage bias. The ions and electrons are accelerated in opposite directions. The ions are accelerated towards the cathode

tube. The ions being accelerated will reach maximum speed at the cathode tube and maintain their maximum speed during passage through the tube. After exiting the cathode tube, they are decelerated and eventually reach a full stop before ramming into the anode dish. Immediately following the full stop, they are accelerated again in the reverse direction toward the cathode tube. In this fashion, they oscillate back and forth along electric field lines many times until they are lost. The electrons are accelerated towards the anode dish. They are lost after reaching the anode dishes.

During this oscillation, the ions reaching a sufficiently high speed will collide and fuse with neutral atoms and with other oscillating ions. And at the same time, the ions ionize background gas, producing secondary electrons. The ionization is the highest as ions reach their maximum speed. On the other hand, as the electrons accelerate toward the anodes, they continuously collide with neutral atoms and ionize background gas. After each collision, their speed is reduced, but the ions are accelerated again. This process repeats itself until the electrons reach the anodes. These newborn electrons and ions soon follow the aforementioned processes.

Viewed macroscopically, the moving electrons form electron jets speeding toward the anodes. The electron jets serve two purposes. First, they are a means to create ions. Second, they confine ions within the jet columns due to their negative space charge.

The role of the cylindrical cathode is threefold. First, it is used to accelerate ions. Second, because the cathode has a cylindrical geometry, it is 100% transparent to the oscillating ions. Therefore, it has no loss of ions or cathode-structure overheating due to direct ion-cathode collisions, which may well be a problem for other cathode configurations used for the same ion-acceleration purposes. Indeed, the reduced cathode bombardment achieved with this embodiment is a major advantage of the present cylindrical design. Third, an optimum length of the cathode cylinder is

critical to an optimum fusion rate, due to the high fusion probability inside the cathode cylinder (i.e., the fusion rate is the highest after fusible ions reach their maximum speed).

The role of the dish anodes are twofold. First, they are used to deflect ions. Second, the dish-shaped reflectors create electric field lines. Ions are guided along the field lines and as a result, ion loss to collisions with the glass wall is reduced.

The operation parameters for a typical cylindrical device are:

- Voltage: 20 kV - 70 kV (The upper limit is set by electrode spacing.)
- Pressure: 3×10^{-3} Torr - 6×10^{-4} Torr
- Current: 2 mA - 5 A (The lower limit is set by the self-sustaining discharge condition, and the upper limit by space-charge limitation. Grid heating is not a deciding factor for determining the upper limit. The 200-mA upper limit for our experiment was set solely by the power supply available. The space-charge limitation is estimated to lie between 2-5 A for a device of the present dimensions.)

The distance in the present device is 9 inches, which allows a maximum discharge voltage up to 60 kV. In general, the longer the distance between anode-cathode electrodes, the higher the discharge voltage. This would in turn allow high reaction rates, due to the rapid increase in fusion cross section with energy, i.e. applied voltage. However, space limitations for various applications set an upper limit to the allowable length of the device.

The advantages of the cylindrical embodiment over the spherical configuration include a somewhat higher yield of neutrons per unit of input power, and reduced bombardment of the cathode grid by ions, thereby reducing the grid temperature and extending grid life.

While the above discussion has stressed operation of the cylindrical device to produce neutrons by use of deuterium gas fill. However, 14.1-MeV neutron production is

possible with a deuterium--tritium fill. Also like the spherical version, 14.1-MEV neutron production with deuterium--helium-3 gas fill is also feasible and attractive for other applications.

Operation of Spherical IEC Generator

In the first preferred embodiment, a 30-cm diameter spherical vacuum vessel 12 made out of 0.48-cm 304 stainless steel was used. The chamber 14 was vacuum-pumped with an 80-liters/second turbo pump backed by a mechanical roughing pump. This achieved a vacuum pressure of approximately 10-7 Torr without baking the chamber. Three different grids were tested. They were made from various sizes of T302/304 stainless steel wire: 0.80 mm, 1.04 mm and 1.30 mm in diameter. All of the grids had a geometric transparency of between 78% and 99%.

Prior to operation, the IEC generator is conditioned to remove absorbed gas impurities, using extended glow discharge operation. Then the vessel 12 is pumped down to approximately 10^{-7} Torr, backfilled with deuterium gas to between 5-20 mTorr and a 10- to 80-kV negative electric potential is applied to the cathode grid 16 to initiate the glow discharge. Driving currents of between 1 mA and 100 mA are employed. The voltage and pressure are generally related by the traditional Paschen voltage-breakdown--pressure relation, where the voltage is a function of a pressure-length product. For the IEC generator, the length in this relation is identified with the distance from the grid to the vessel wall, as opposed to the grid diameter.

The diagnostics employed included pressure sensors and current and voltage meters on the cathode power supply. A BF_3 proportional counter, placed 40 cm from the IEC chamber and surrounded by a 9-cm-thick polyethylene cylinder (for thermalization of neutrons), was used to measure neutron source strength. This neutron-counting system allows neutron detection over a wide range of fluxes: from high counting rates (approximately 10^5 cpm) to low counting rates, ultimately limited by the background rate of approximately 10

cpm. Interference by induced electronic noise was minimized by electronically shielding the preamp and cables. The neutron detection system was calibrated in situ with a 1-Ci PuBe source.

In another test, the stainless steel grid was replaced with a grid made of molybdenum. The openings were approximately identical to that of the stainless steel grid. The pressure was adjusted to between 20 mTorr to 3 mTorr, and the voltage and current varied from 2 kV to 80 kV and 10 mA to 15 mA, respectively. Results were consistent with prior stainless-steel grid studies. However, with a larger power supply, even higher currents could be used without overheating the molybdenum grid. This, in turn, would allow a significant increase in the neutron source rate.

Results

The glow discharge operation of the IEC generator in its spherical embodiment can be categorized according to three distinctive discharge modes. These are the Central Glow mode, as shown in FIG. 4; the Star mode, as shown in FIG. 5; and the Halo mode, as shown in FIG. 6. The names are descriptive of the visual appearances of the light emitted from the discharges, as shown in FIGS. 4-6. Each mode is associated with a different potential well structure, hence neutron production rate, for given operating parameters, i.e., cathode current and voltage. Each requires a unique combination of operating parameters, i.e., voltage, current, pressure and grid parameters.

Applicants' 1992 paper reported their discovery of three types of discharges which could be produced by a spherical inertial electrostatic confinement generator. These were called the Central Glow mode, illustrated in FIG. 4, the Star mode illustrated in FIG. 5 and the Halo mode illustrated in FIG. 6. The names are descriptive of the visual appearance of the light emitted from the discharges. Further developments based on that work have resulted in the invention of the present application.

The ability to select the operating mode is an important aspect of this invention. The design of the grid plays a key role in mode selection. The Central Glow mode is the type of operation described by earlier workers (Farnsworth and Hirsch). In the Central Glow mode as shown in FIG. 4, a ball-shaped glow is produced in the center of the sphere. This is the mode described in the Farnsworth and Hirsch patents cited above. To produce it, these earlier workers in the field required an ion source such as ion guns or an ion source grid or an electron emitting cathode (which was only a theoretical suggestion by Hirsch). Applicants' previously cited 1992 paper disclosed production of the Central Glow mode by a device with a spherical cathode grid 36 mounted around the original cathode grid 16 and biased negatively with respect to the original cathode by about 25%. In it, the grid is made as spherical as possible, composed of many fine grid wires with many openings to obtain a large geometric transparency and a reasonably uniform and spherically symmetric flow of ions. In such operation, the grid transparency is a key parameter: since ions flow almost uniformly through the grid, a fraction of the current is intercepted and lost to the grid wires. The higher the geometric transparency of the grid, the lower the loss fraction of ions--increasing the ion recirculation rate. The reaction rate in the center spot is correspondingly increased, and the heating and sputtering of the grid by ion bombardment is reduced. Thus, developing and optimizing such grid designs were the primary goals of earlier workers in the field. The use of an extremely transparent grid faces technological problems, however. Such a grid has little structural strength. Further, should active cooling be desired, the use of a tubular grid to allow coolant flow forces larger grid wire diameters, reducing transparency. For similar operating voltages and currents, this mode gives only about one-third of the neutron output per unit power input compared to the Star mode.

Our discovery of the Star mode completely changes this emphasis on fine grid wires and high transparency as the major design criteria. To create the Star mode, a grid is constructed such that the grid opening diameter is a significant fraction of the major circumference of the grid. This causes a local depression of the potential surface. (This depression is to be avoided to create the Central Glow mode.) This depression in turn causes the ion flow to become focused, forming the characteristic radial ion beams or "spokes" of the Star mode. The existence of these ion beams was confirmed by superimposing a magnetic field and observing the deflection of the beam. With this configuration, the ions flow primarily through the grid openings, so interception by grid wires ceases to be a major consideration, and grid transparency no longer must be the key grid design factor.

The Star mode, as shown in FIG. 5, was studied extensively and unless otherwise noted, all of the neutron measurements were taken in this mode. It is distinguished by microchannels or "spokes" radiating outward from a center spot 38. As verified by magnetic deflection experiments, the spokes are primarily composed of ion beams, aligned so that they pass through the center of the openings delineated by the grid-wires. At the center of the volume circumscribed by the cathode grid 38, where the spokes intersect, a bright spot is formed. This mode is very efficient for neutron production, since the ion "spokes" pass through the grid openings, creating an effective grid transparency that is greater than its geometric value. This increased transparency allows numerous passes of ions through the center spot 38 before being intercepted by the grid. This in turn increases the ion density in the center spot, hence the neutron emission rate, while reducing ion bombardment, sputtering and erosion of the grid. The Star mode is typically obtained in the IEC generator at lower operating pressures (<10 mTorr) and higher voltages (>30 kV), using a carefully

formed grid with good sphericity and high geometric transparency, generally greater than 93%.

Operation in the Star mode requires a combination of pressure, volume, and current parameters and a grid design which gives sufficient local perturbation of the electric field to cause ions to deflect into channels. Such perturbations are achieved by a grid hole size that provides openings which cover a significantly larger portion of the total surface area of the grid sphere. Stated another way, the percentage of the grid sphere surface which is occluded by the grid is to be significantly reduced. The range of such reductions in grid occlusion appear to be desirably in the range of 2.5% to 7%. For example, from a basic grid occlusion of 3% with 97% transparency, a seven percent reduction in occlusion would lead to grid occlusion of 2.79% with transparency of 97.21%. Once the process is initiated, the self-field forces further aid the process by further constricting and maintaining the ion beams.

There are several ways to design the grids for the Star mode which are described below.

The first variation is a "globe" grid design in which the solid wires follow the longitudinal and latitudinal lines of a globe or sphere. This design has larger holes near the equator and smaller holes near the poles.

The second variation, a "geodesic" grid, uses a geodesic dome type of pattern in which the solid wires are all on geodesic lines. In the geodesic design there are also size differences in the holes. However, the large holes are spread evenly around the sphere and not localized near the equator as in the globe design.

A third design is an "orthogonal" design which has the most evenly sized holes. In this design all intersecting circles of solid wires are orthogonal to the others at their intersections.

The exact range and combination of grid parameters to achieve the desired operational modes are still under investigation, but successful designs that create the Star

mode have the parameters discussed below. These grid designs all operate satisfactorily in the pressure, voltage, and ion current ranges discussed earlier in this disclosure. However, as stated previously, operation in the Star mode requires a sufficient local perturbation of the electric field to cause ions to deflect into channels. These perturbations are achieved by using openings between the grid wires which are of sufficient size to cause this perturbation, but not so large as to distort the extracted ion trajectories. Three different grid designs (globe, geodesic, and orthogonal, described earlier) which produce the Star mode (and also the Halo mode) were studied. All designs used 0.0051-cm diameter grid wire with the overall grid diameters ranging from 3.75 cm to 45.0 cm. The Star mode was obtained with all designs providing >93% geometric transparency. The smaller major diameter designs had transparencies towards the lower end of this range, but still induced the Star discharge mode.

The ratio between the height h of the grid opening surface to the sphere surface and the sphere radius R_c determines the degree of depression of the potential surface, in turn causing focusing through the opening, i.e. beam formation. It follows that $e1<h/R_c<e2$ is the criterion for Star formation. If h/R_c approaches $e1 = 0$, the potential surfaces are virtually spherical, causing the Central Glow mode to be initiated. On the other hand, if h/R_c becomes too large, focusing is destroyed (or if done locally, as described later, the large local depression creates an electron jet, forming the Halo mode.) The Star mode has been successfully formed over a broad range of $e1 = 0.01$ to $e2 = .15$, using .005-cm-wide stainless-steel grid wires. These limits are approximate, since a number of other factors also influence discharge mode formation, e.g. the secondary electron emission coefficient of the grid wires.

Consistent with the improved "effective" transparency achieved by the Star mode, with our invention the neutron emission rate in this mode is approximately double that for equivalent (same current, voltage, and

pressure) Central Glow mode operation. However, for the future development of higher-current, i.e. higher neutron-rate, devices, the ability to maintain a high "effective" transparency even with thicker, actively cooled grid structures (corresponding to a reduced geometric transparency) may be the key advantage of Star mode operation.

FIG. 6 illustrates the final, quite unique mode, the Halo mode. This is initiated in the same manner as the Star mode, but usually at lower pressures, and hence, higher cathode voltages. However, to achieve the Halo, a physical modification of the grid structure 16 is necessary. The transition to the Halo mode is accomplished by enlarging one or more of the grid openings (i.e., physically removing the wire section separating adjacent openings). This is done in either a globe, geodesic, or orthogonal-type grid. Cutting these large holes leads to a larger perturbation in the electric field. The size of one of the grid openings is approximately doubled, as compared to adjacent openings. This causes a flow of electrons out of the center volume (electron jet) under which circumstance the Halo mode develops. Then a strong jet of electrons is observed to flow through the enlarged opening(s). The existence of this electron jet was confirmed experimentally by superimposing a magnetic field and observing the deflection of the electron beam. Up to six jets have been created on opposite faces of the grid. The jet is thought to result from potential surface distortions; however, more work is needed to fully understand the mechanisms involved. The jet in turn creates new ions by collisional ionization of the background neutrals. The resulting ion and electron flows causes a complete redistribution of space charge, thus forming a new potential well structure characterized by a bright central glow and an outer glowing halo region. A bright white, spherical halo is formed concentric to the cathode grid with a bright spot at the center. Accordingly, we have termed this operational mode the Halo mode. The Halo has always been accompanied by the electron jet, noted above, which is

believed to be a fundamental characteristic of the mode. Because of the asymmetry involved in this mode, it is restricted to neutron applications where isotropic emission is not essential. The Halo mode generally offers a factor of 1.5 to 3 times higher rates of neutron emission per unit input power than does the Star mode. This is believed to be due to the development of a unique potential-well configuration in the Halo mode that is efficient for trapping and recirculating ions.

Such a configuration is consistent with calculations for cases where the potential diagram has a double well-type structure which is predicted to trap ions in the inner well, increasing the reaction rate. Theoretically such potential well structures trap beam ions, increasing the reaction rate. Consistent with this prediction, the neutron emission rate from our device increases threefold in the Halo mode, compared to Star mode operation at the same pressure, voltage and ion current. Despite the lower neutron rate, we have generally favored using the Star mode to avoid the asymmetry and possible wall damage arising from the electron jet formed in the Halo mode. If alternate ways were found to initiate the Halo mode without creating the electron jet, this might become the preferred operational mode.

Table I. Ratio of grid opening size to total grid surface area. Higher ratios are associated with enhanced ion channel formation in the Star mode.

<u>GRID CHARACTERIZATION FOR Central Glow MODE, STAR MODE, AND HALO MODE IN TERMS OF THE POTENTIAL SURFACE PERTURBATION</u>

Parameter	Definition
A_o	Planar area of a grid opening.
A_t	Total surface area of spherical cathode.
D	Diameter of the cathode grid.
h	Height of grid opening surface to sphere surface.
P	Deviation of cathode grid from a perfect sphere, defined as h/R_c.

P_g Global perturbation h/R_c as the perturbation in the Star mode.

P_l Local perturbation h/R_c as the perturbation of the large holes in the Halo mode/

- Range of h/R: 0<h/R<1 (h/R=1, the hole size of which is half of a sphere)
- Central Glow Mode: 0<Pg<0.01 (Central Glow Mode has been tested to exist at Pg=0.0028 in Globe grid.)
- Star Mode: 0.01<Pg<0.286 (The Pg=h/R=0.286 is the perturbation value for a three-ring construction. No test has been done to verify the existence of Star Mode at this value. A maximum value of Pg=0.15 in Geodesic Grid and a minimum value of Pg=0.013 in Globe grid have been tested to show Star Mode.
- Halo Mode: 0.0192<Pl<0.076, Pl/Pg>4, max. number of electron-jet <2.
  0.0192<Pl<0.076, Pl/Pg>16, max number of electron-jet <4.
  0.0192<Pl<0.076, Pl/Pg>64, max number of electron-jet <6.

(By using the h/Rc definition for perturbation, the perturbation is reduced by approximately 4 times when a hole-size is cut into half.)

Grid Perturbations

	Globe			Geodesic				Orthogonal		
Ao/At	0.0226	0.0066	0.0014	0.0694	0.0295	0.0198	0.0175	0.0255	0.0113	0.0079
D	7.5	45	15	3.75	7.5	19.5	29.5	7.5	15	40
At	176.71	6361.7	706.86	44.179	176.71	1194.6	2734	176.71	706.86	5026.5
Ao	3.9937	41.987	1	3.066	5.2131	23.653	47.844	4.5062	7.9875	39.71
h/R	0.0463	0.0133	0.0028	0.1501	0.0609	0.0404	0.0356	0.0524	0.0229	0.0159

Two grid-wire materials have been studied experimentally, stainless steel and molybdenum. Other possible materials exist which could increase the lifetime and performance of the grid. Table II. lists some candidate materials and their properties. Desirable properties are a high melting point, high secondary electron coefficient, low electrical resistivity, high thermal conductivity, and low sputtering yield. Tungsten is seen to best suit these goals, but its poor ductility makes tungsten grid fabrication difficult and expensive. Consequently, the optimum choice may be a compromise between desirable properties and ease of manufacturing.

Table II. Performance parameters of various grid materials.

	Stainless Steel 304	Vanadium	Molybdenum	Tungsten
Melting Point (°C)	1427	2160	1887	3680
Secondary Electron Coefficient	1.30	-	1.25	1.40
Electrical Resistivity at 273° K (ΩM)	$9.7x10^{-8}$	$24.8x10^{-8}$	$5.2x10^{-8}$	$5.65x10^{-8}$
Thermal Conductivity (W/m°K)	25.1	30.7	138.0	174.0
Sputtering Yield at 50 keV (atoms/ion)	$<10^{-2}$	$<10^{-2}$	$<10^{-2}$	$<10^{-3}$
Ductility	good	fair	fair	poor

Two other interesting materials not shown in Table II are beryllium and aluminum. The sputtering yield of beryllium is about a factor of 10 below that of iron. An additional benefit of beryllium is its high secondary-electron emission coefficient. Aluminum also exhibits both a lower sputtering rate and a higher electron yield, as compared to stainless steel. Neither of these materials

could be used as the structural base for the grid. However, a thin coating of either on a substrate of stainless steel or one of the other materials in the table could be very attractive. With an aluminum-coated grid, an order-of-magnitude increase in neutron output is anticipated.

Another way to improve the performance of the grids is to construct them from ribbon-shaped wires, rather than regular cylindrical-shaped wires. Ribbon-shaped wires have rectangular cross sections, hence a greater surface area, as opposed to the circular cross sections of ordinary wire. The flattened ribbon shape can thus increase the thermal radiation emission capability of the grid, while maintaining the same grid transparency.

Plots of measured neutron source strength versus cathode current in the IEC generator are shown. in FIG. 8 for different cathode voltages and currents. The neutron yield increases linearly with current, and scales strongly with voltage. The scaling with voltage roughly corresponds to the variation of the fusion cross section with energy, i.e., approaches an exponential increase in this range of voltages. For the practical applications of interest here, we have limited operation to about 80 kV, so that more complex high-voltage handling equipment is avoided. With this voltage limit, the maximum current is then set by the power heating limits for the grid. It is seen from FIG. 8 that the target source rate of 106 D-D n/s is achieved at 70 kV with a current of about 15 mA.

Based upon the measured data, parameters for an optimized version of the inventive IEC generator, designed for production of about 106 D-D neutrons/second are a cathode voltage of 70 kV, a cathode current of 15 mA, a vessel diameter of 30 cm, a grid cathode diameter of 3.75 cm, geometric grid transparency of 95% and background pressure of deuterium of 8 mTorr.

The preferred device is restricted to 70 kV for convenience. If higher neutron yields are desirable for a particular application, the voltage could be increased with

the use of an appropriate power supply. Such an extrapolation is not straightforward, however. In the Star mode, the operating voltage is an inverse function of the background pressure. Thus, an increase in the operating voltage requires a decrease in the background pressure. However, the neutron yield still increases, since the increase in cross section due to higher ion energies at the higher voltage more than offsets the decrease in background pressure. Neutron yields can also be increased by increasing the input current. In any case, the input power, i.e. voltage current product, must be limited to values set by the heat load limits on the grid. The latter limits are a function of grid geometry, construction material, and whether or not an active cooling system is used.

FIG. 2 illustrates the production of a positive potential well inside the center of the cathode grid 16. The spherically converging ions constitutes the formation of a single positive potential well inside the cathode grid 16. We can see in FIG. 2 that the negative electric potential increases from the vessel 12 to the grid 16. It then drops off rapidly towards the center spot. If sufficient current is passed through the cathode 16, the collective space charge of the ions will form a virtual anode. This anode will attract electrons generated from ion collisions with the cathode grid structure and from ionization of background gas inside the cathode grid structure, which in turn can create a virtual cathode inside this virtual anode. This, in effect, forms a double potential well. The advantage of such a structure is that ions trapped in the double potential well recirculate through the center of the well, enhancing collisions, i.e. fusion reactions. The virtual cathode serves the same purpose as the physical grid, but has the key advantage of having a 100% transparency. Indeed, the enhanced neutron production in the Halo mode and the Star mode is due to some extent to the formation of a potential structure of this type.

The IEC generator also potentially represents an important MeV proton source. Indeed, one of the diagnostics, used in the D-D device studies described here for neutron production, was a solid-state detector for measurement of the 3-MeV proton also produced by the D-D reaction. Since the reaction branches for D-D are roughly equally probable, the neutron and proton source strengths are equal. The energetic protons easily escape from the kV confinement fields, making their use for external irradiation applications feasible. Yet higher-energy (14 MeV) protons can be produced in a similar fashion by using a fill gas mixture of deuterium-helium 3, which undergoes a fusion reaction yielding a 3.5 MeV alpha particle and a 14.1 MeV proton. Through slight modification, the IEC generator can be used as a proton generator.

As a proton generator, to reduce proton losses due to the charge exchange effects, the operating voltages need to be set even higher than that for the IEC as a neutron generator. Such operation offers added benefits: (1) any increase in the cathode voltage enhances the proton production considerably (more so that for D-D reaction) due to the strong increase of the D-3He reaction cross section with energy, (2) the higher the ion energy the smaller the probability for proton losses due to charge exchange (again, this is due to the energy dependence of the reaction cross section involved). Thus, a larger number of protons will make it to the periphery of the chamber where they can be used. Examples of techniques for this use and possible applications include:

(1) for bombardment of target materials, in form of gases or solids inside or outside the confining chamber. A thin wall honey-comb-membrane, for the purpose of containing a gaseous or solid target may be necessary. Such a structure provides structural strength but still provides a thin "window" region between the comb "chambers" through which protons can easily penetrate without excess energy loss. A

membrane of this type with one side open could be used for the chamber wall with external targets.

(2) for H_2 production by radiolysis using an external cell of steam and,

(3) to produce direct electrical output for a compact fusion power source for extraterrestrial exploration. In this case a proton "collector" structure is employed for direct conversion of kinetic energy to high voltage electricity.

Another option to increase the proton rate would be to operate the device in a pulsed mode at high injected current. The number of protons generated per input power that will participate in activating the target will be less than the steady-state mode mentioned above.

In summary, operation with a stainless steel grid employing only radiative cooling and a modest 70-kV power supply) provides a steady-state source strength of about 1.2×10^{6} D-D n/S or about 1.2×10^{8} D-T n/s. Much higher yields could be obtained if tungsten grids were used or if the grids were actively cooled, e.g., via water cooling in a tubular design. A reasonable target for such designs would be 10^{8} D-D n/s or 10^{10} D-T n/s. Still further modifications to achieve higher currents (e.g., a pulsed design with capacitors) could, in principal, achieve even higher neutron yields.

Thus, there has been provided in accordance with the invention an inertial-electrostatic confinement particle generator that fully satisfies the objects, aims and advantages set forth above. While the invention has been described in conjunction with specific embodiments thereof, it is evident that many alternatives, modifications and variations will be apparent to those skilled in the art in light of the foregoing description. Accordingly, it is intended to embrace all such alternatives, modifications and variations as fall within the spirit and broad scope of the appended claims.

What is Claimed is:

1. Apparatus for generating neutrons and protons comprising:

(a) anode means comprising a substantially spherical vacuum vessel,

(b) cathode means comprising a substantially spherical structure, permeable to gas and to ions, disposed within said anode means,

(c) means for removing gas from said vacuum vessel and said cathode means to reduce the pressure therein to less than about 20 mTorr,

(d) means for introducing controlled amounts of reactive gas into said vacuum vessel and said cathode means,

(e) means for applying an electric potential between said anode means and said cathode means to produce ions between said anode means and said cathode means, and

(f) said cathode means comprising a spherical hollow grid which is self supporting and without internal supports and is supported centrally of said spherical vacuum vessel by supporting members outside of said grid.

2. Apparatus according to claim 1 wherein said grid provides openings therethrough to permit entry of said ions within said spherical structure and interaction with said reactive gas therein to produce neutrons and protons.

3. Apparatus according to claim 1 wherein said grid has a geometric transparency of between 78% and 99%.

4. Apparatus according to claim 1 wherein said grid has a geometric transparency of less than 80%.

5. Apparatus according to claim 1 wherein said grid has a geometric transparency of more than 97%.

6. Apparatus according to claim 1 wherein said reactive gas is deuterium.

7. Apparatus according to claim 1 wherein said reactive gas is a mixture of deuterium and tritium.

8. Apparatus according to claim 1 wherein said reactive gas is a mixture of deuterium and helium-3.

9. Apparatus according to claim 1 wherein said means for applying electric potential applies a negative potential to said cathode of between 30 kV and 80 kV.

10. Apparatus according to claim 1 wherein said means for applying electric potential employs driving currents between 1 mA and 100 mA.

11. Apparatus according to claim 1 wherein said grid is formed of cylindrical wires.

12. Apparatus according to claim 1 wherein said grid is formed of flat ribbons.

13. Apparatus according to claim 1, further comprising a second substantially spherical hollow grid surrounding said cathode means and means for applying to said second grid a negative electric potential of about 20% to 30% of the negative potential of said cathode means.

14. Apparatus according to claim 2 wherein the size of at least one of said openings through said grid is about twice the size of adjacent openings therethrough.

15. Apparatus according to claim 1 wherein said reactive gas is continuously introduced into said vacuum vessel and extracted therefrom.

16. Apparatus according to claim 1 wherein said vacuum vessel can be filled with a predetermined amount of reactive gas and then disconnected from said means for removing gas therefrom to permit operation independently of connection to said means.

17. Apparatus according to claim 1 wherein the solid parts of said grid are on the longitudinal and latitudinal lines of a sphere.

18. Apparatus according to claim 1 wherein the solid parts of said grid are on geodesic lines of a sphere.

19. Apparatus according to claim 1 wherein the solid parts of said grid are on lines of a sphere which are orthogonal to one another at their intersections.

20. Apparatus according to claim 1 wherein the pressure in said vacuum vessel is reduced to less than 10 mTorr and said electric potential is greater than 30 kV.

21. Apparatus according to claim 2 wherein the size of at least one of said openings is about twice the size of adjacent openings.

22. Apparatus according to claim 1, further including a proton detector outside of said spherical vacuum vessel to provide a measurement of neutron emission rate.

23. Apparatus for generating neutrons and protons comprising:

(a) a substantially cylindrical vacuum vessel;

(b) anode means comprising a pair of anodes adjacent opposite ends of said vacuum vessel which are concave toward the central region of said vessel;

(c) cathode means comprising a substantially cylindrical structure within said vacuum vessel between said anodes and defining a central volume;

(d) means for introducing controlled amounts of reactive gas into said vacuum vessel and said central volume; and

(e) means for applying an electric potential between said anode means and said cathode means to produce ions within said central volume.

24. Apparatus according to claim 23, including means for removing gas from said vacuum vessel and cathode means to reduce the pressure therein to about 10^{-7} Torr prior to introducing said reactive gas therein.

25. Apparatus according to claim 23 wherein said cathode means comprises a hollow cylindrical grid open at both ends thereof adjacent said anodes and surrounding said central volume.

26. Apparatus according to claim 25 wherein said grid provides openings therein to permit entry therein of said reactive gas and exit therefrom of neutrons and protons produced in said central volume.

27. Apparatus according to claim 25 wherein said grid is self supporting and without internal supports and is supported centrally of said vacuum vessel by supporting members outside of said grid.

28. Apparatus according to claim 23 wherein said vacuum vessel is of a non-electrically conductive material.

29. Apparatus according to claim 25 wherein said grid has a geometric transparency of between 78% and 99%.

30. Apparatus according to claim 25 wherein said grid has a geometric transparency of less than 80%.

31. Apparatus according to claim 25 wherein said grid has a geometric transparency of more than 97%.

32. Apparatus according to claim 23 wherein said reactive gas is deuterium.

33. Apparatus according to claim 23 wherein said reactive gas is a mixture of deuterium and tritium.

34. Apparatus according to claim 23 wherein said reactive gas is a mixture of deuterium and helium-3.

35. Apparatus according to claim 23 wherein said means for applying electric potential applies a negative potential to said cathode of between 30 kV and 80 kV.

36. Apparatus according to claim 23 wherein said means for applying electric potential employs driving currents between 1 mA and 100 mA.

37. Apparatus according to claim 25 wherein said grid is formed of cylindrical wires.

38. Apparatus according to claim 25 wherein said grid is formed of flat ribbons.

39. Apparatus for generating neutrons and protons, comprising:

(a) a vacuum vessel;

(b) anode means substantially within said vacuum vessel and concave towards a central region of said vacuum vessel;

(c) at least one cathode wire grid defining a central volume and concave towards a central region of said vacuum vessel, said cathode wire grid is permeable to gas and to ions and disposed between said anode means;

(d) means for introducing controlled amounts of reactive gas into said vacuum vessel and said central volume to obtain an internal pressure of the vacuum vessel; and

(e) means for applying an electric potential between said anode means and said cathode wire grid to produce a glow discharge caused by ions produced between said anode means and said cathode wire grid;

(f) wherein the glow discharge is substantially determined by design criteria of said cathode wire grid and said internal pressure of the vacuum vessel.

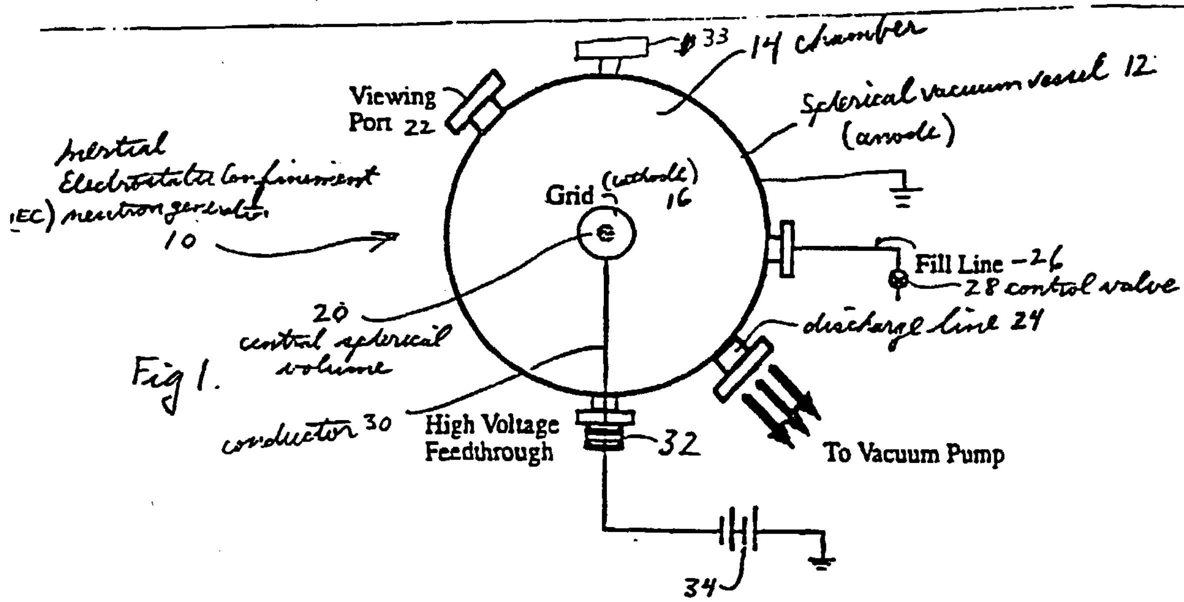

33
14 chamber
Viewing Port 22
Spherical vacuum vessel 12 (anode)
Inertial Electrostatic Confinement (IEC) neutron generator 10
Grid (cathode) 16
Fill Line - 26
28 control valve
20 central spherical volume
discharge line 24
conductor 30
High Voltage Feedthrough
32
To Vacuum Pump
34

Fig 1.

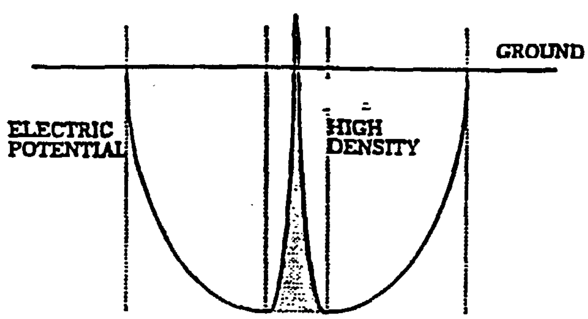
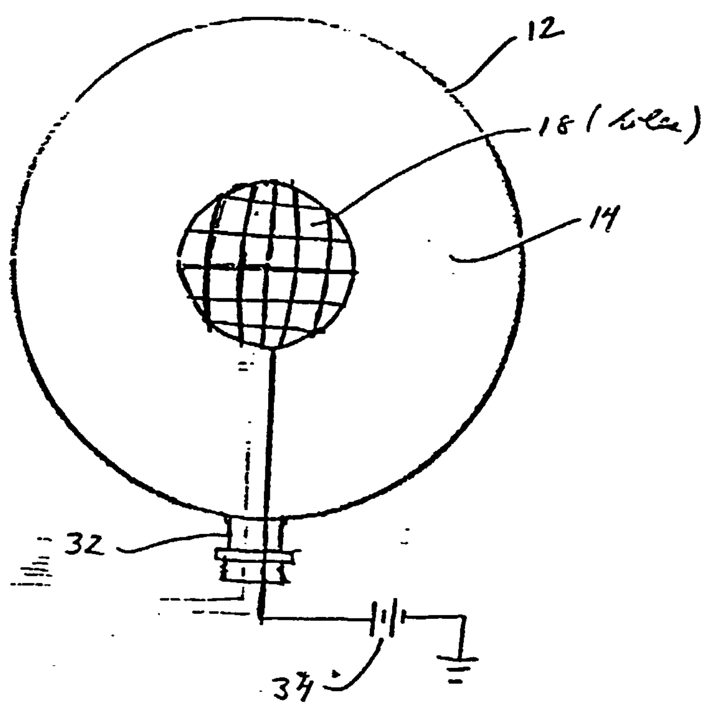

GROUND
ELECTRIC POTENTIAL
HIGH DENSITY

Fig 2.

Fig. 3



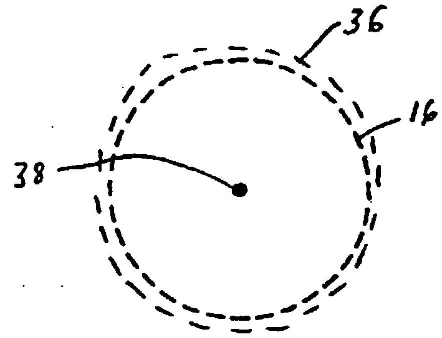


Fig 4

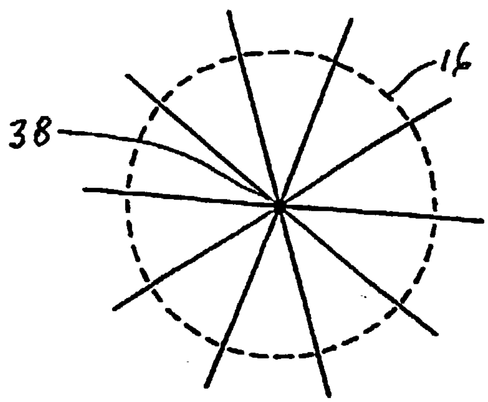


Fig 5

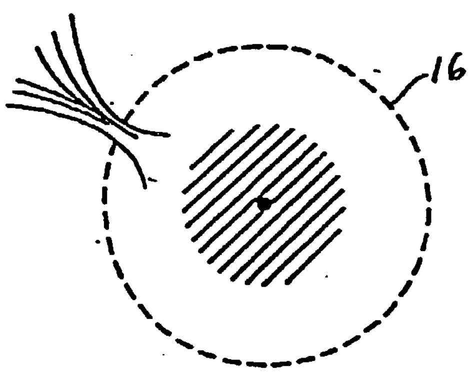
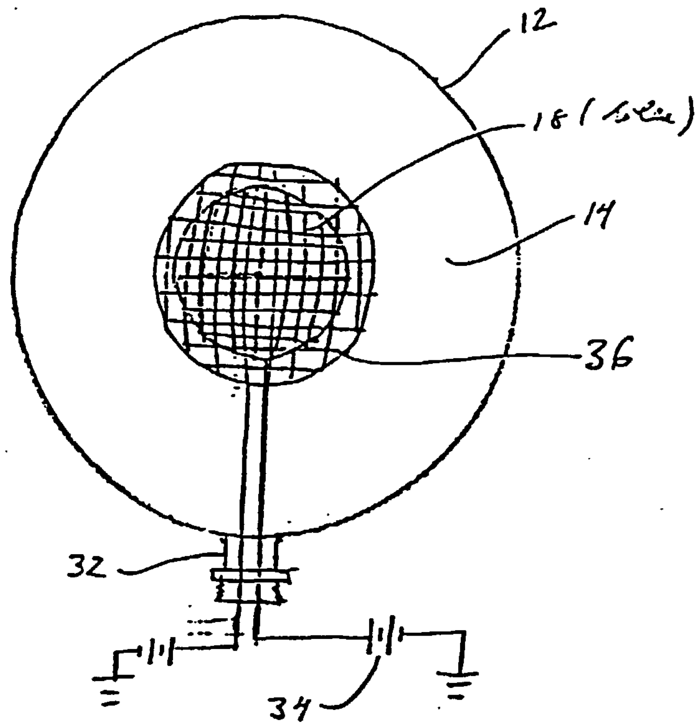


Fig 6


12
18 (solid)
14
36
32
34

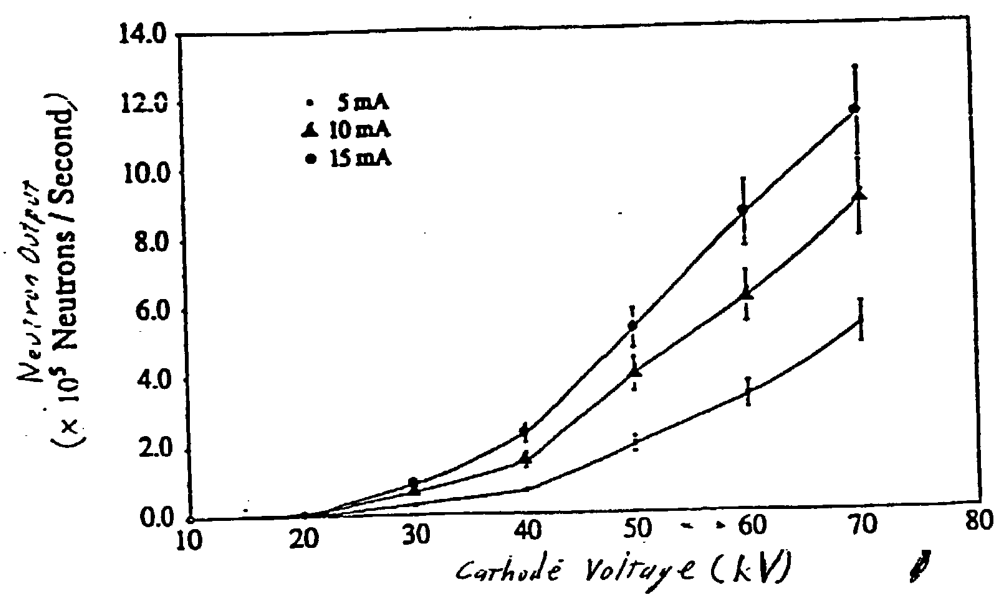

14.0
12.0
10.0
8.0
6.0
4.0
2.0
0.0
• 5 mA
▲ 10 mA
● 15 mA
Neutron Output
(× 10⁵ Neutrons / Second)
10
20
30
40
50
60
70
80
Cathode Voltage (kV)

Fig. 8

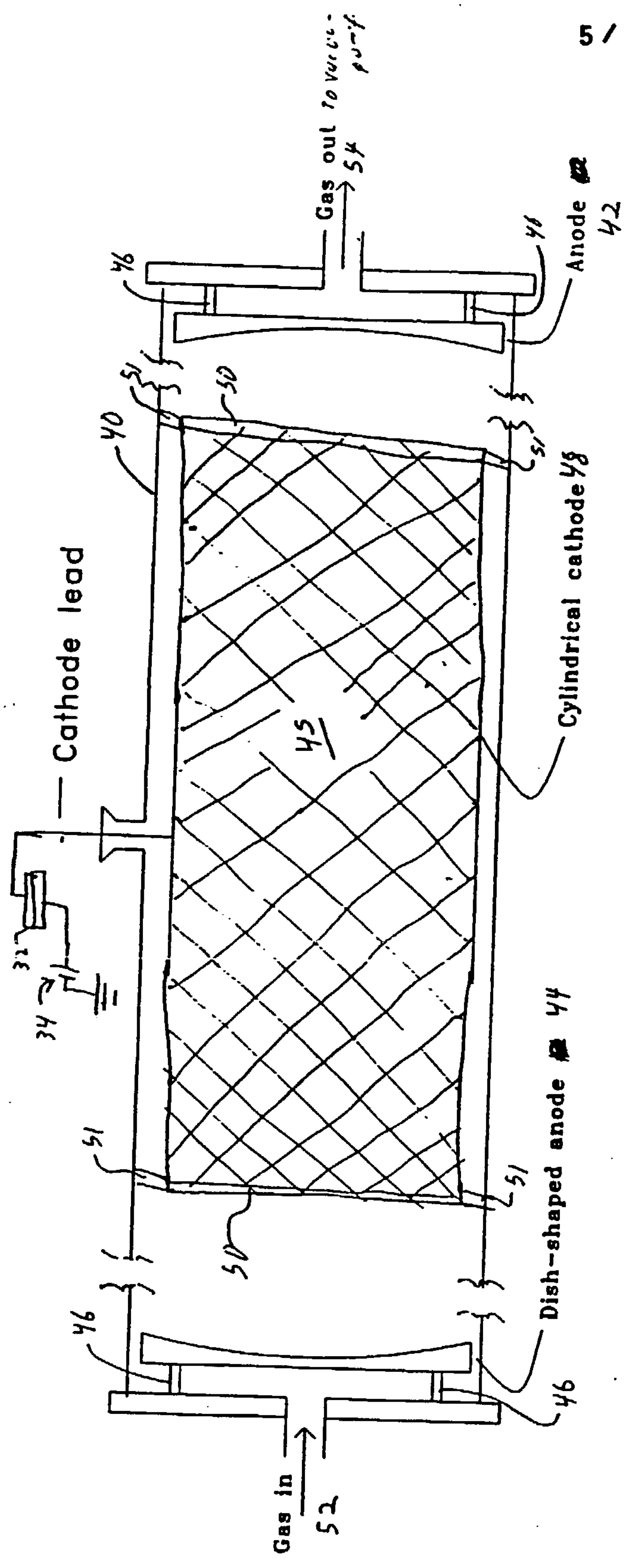

Gas out to vacuum pump
54
Anode 42
46
48
40
51
50
Cathode lead
45
Cylindrical cathode 48
32
34
51
50
Dish-shaped anode 44
46
46
Gas in
52

FIG. 9

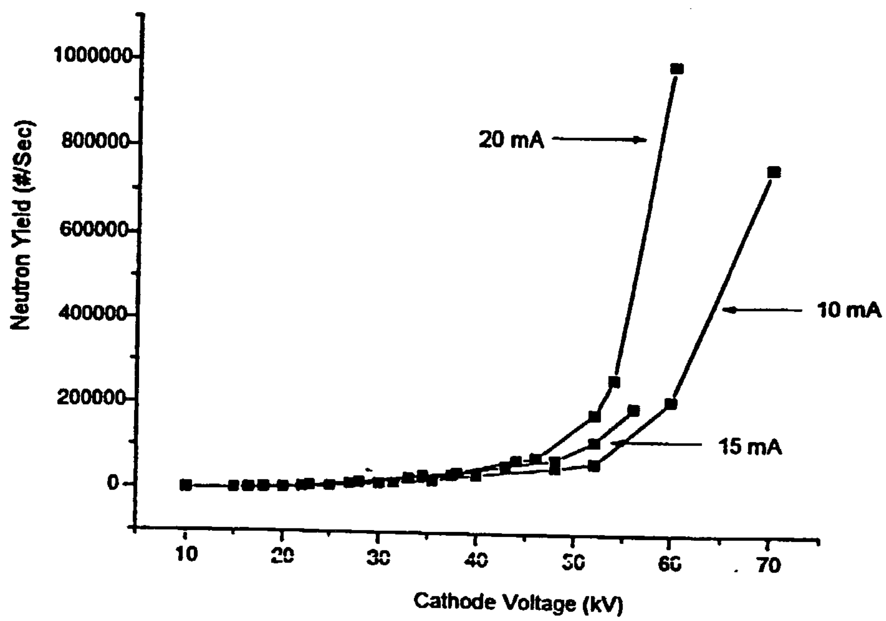

1000000
800000
600000
400000
200000
0
Neutron Yield (#/Sec)
20 mA
10 mA
15 mA
10
20
30
40
50
60
70
Cathode Voltage (kV)

Fig. 10